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ABSTRACT

Highly-coupled couplers (3-dB and 6-dB) are necessary for a wide range of millimeter-wave coplanar circuits. The high line-to-line capacitance required for these couplers is impossible to achieve with thin-film planar coupled lines. Using 80 μm-thick conductors patterned using a 3-D x-ray micromachining technique, we have successfully demonstrated a 15 GHz 6-dB coupler and a single-section coupled-line BPF that utilizes a 3-dB coupler geometry.

INTRODUCTION

Millimeter-wave and microwave integrated circuit passive devices are commonly realized with coplanar waveguide circuitry. Highly-coupled coplanar couplers (3-dB and 6-dB) are necessary for a wide range of millimeter-wave circuits including: balanced amplifiers, balanced mixers, and phase shifters. The high line-to-line capacitance required for 3 to 6 dB coupling is nearly impossible to achieve with planar coupled lines. In this effort, we demonstrate the necessary increase in capacitance through the use of thick-metal coupled lines possessing well-defined vertical sidewalls.

Deep x-ray lithography (i.e. LIGA) may be used to electroplate low-loss [1] metal-on-dielectric passive components with conductor thicknesses > 0.5 mm, extremely high-aspect ratios (defined as height of structure to gap width), and ~90° sidewall slopes [2,3]. Finite-difference analysis of LIGA coplanar coupled-line devices demonstrates that extremely high (> 3 dB) coupling levels may be achieved without difficulty using this process.

Two LIGA CPW coupled-line devices were designed, microfabricated on quartz, tested, and analyzed to demonstrate the performance of this novel geometry: a 15 GHz 4-port 6-dB coupler, and a single-section phase-velocity compensated bandpass filter that utilizes a 3-dB coupler structure.

6-DB COUPLER

A 4-port 15 GHz quarter-wave CPW coupled-line device was designed for Z_0=50 Ω and 6-dB coupling. The port labeling is as follows: port 1 is input, port 2 is thru, port 3 is coupled, and port 4 is isolated. The 6-dB geometry was chosen because the corresponding physical geometry allows for high fabrication yield. The length of the quarter-wave section was designed to be the arithmetic average of the two modes' effective $\lambda/4$ at 15 GHz (quartz ε_r=3.81). A finite-difference program was used to solve for the required quasi-TEM cross-section geometry (Fig. 1 & Table I).

The coupler and TRL calibration standards were fabricated on 420-μm thick quartz with nickel conductors (Fig. 2(a) & 2(b)). Nickel was used for this trial because of its high processing yield, although gold or copper may also be plated. In the LIGA fabrication process described in a previous publication [4], a multilayer metal thin-film is applied to the substrate to form a metal seed layer for subsequent electroplating. A PMMA resist (e.g. Lucite®) up to 1 mm in thickness is laminated

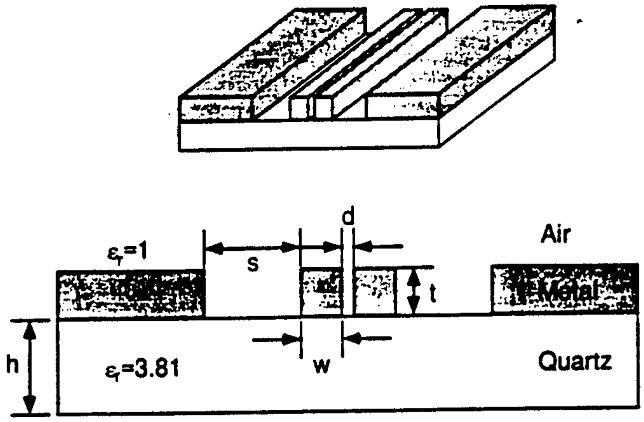

Fig. 1. Cross-section schematic of the CPW coupled-line geometry with dimension labels.

Parameter	6-dB Coupler	3-dB Filter Section
w	188 μm	109 μm
d	39 μm	17 μm
s	100 μm	150 μm
t	80 μm	80 μm
h	420 μm	420 μm
coupling	6 dB	3 dB
Z_{0e}	86.74 Ω	120.7 Ω
Z_{0o}	28.82 Ω	20.73 Ω
ε_{re}	2.06	2.07
ε_{ro}	1.76	1.5
length	3.645 mm	3.475 mm

Table I. Geometric parameters for the CPW coupled-line devices.

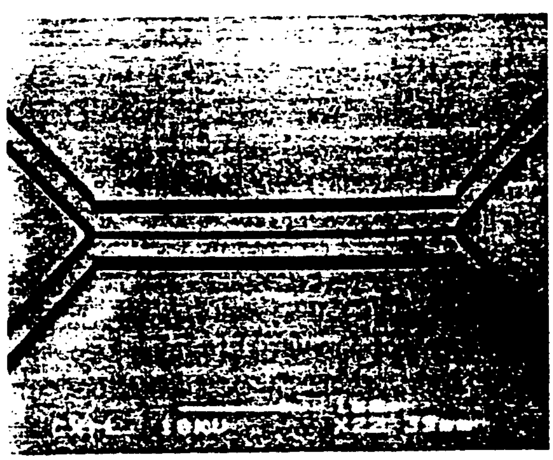

Fig. 2(a). SEM micrograph of a microfabricated thick-metal 6-dB CPW coupler.

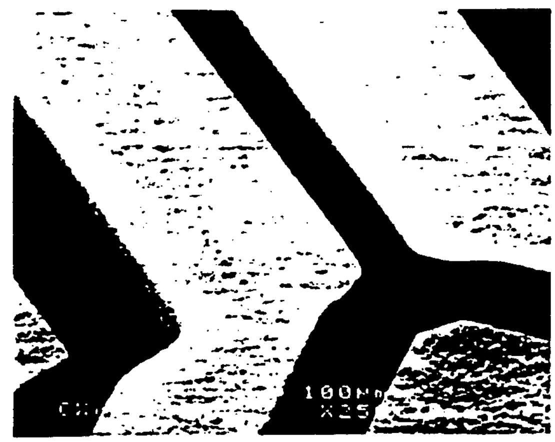

Fig. 2(b). SEM micrograph of the coupling junction in a thick-metal 6-dB coupler.

to the thin-film and patterned using synchrotron x-ray radiation sourced from a particle accelerator. After PMMA development, metal is electroplated into the resist pattern recesses and the PMMA is removed. The metal thin-film is etched away to electrically isolate the plated structures. The final electroplated conductor thickness is approximately 90 μm (~11% error). Air bridges were wirebonded across the device, although they could be added using standard integrated circuit fabrication techniques.

An HP 8722C ANA TRL calibration procedure was followed. Air coplanar probes (Cascade ACP40 probes) and a CPW transmission line transition were used to communicate with the DUT. The 4-port device was terminated by 50 Ω loads through ACP40 probes on the unused ports. The load termination reflection coefficient at the two unused ports was between -12 dB and -25 dB over the test bandwidth. It is possible to rigorously calibrate out the load mismatches present when testing an N-port device with a 2-port 50 Ω calibrated ANA and this will be done in future work [5]. The magnitude and phase of all 16 S parameters were measured and compared with theoretical responses computed using Hewlett-Packard Microwave Design System (MDS) software.

The shape and level of the coupled-port

S-parameter (S_{31}) response indicate that -6.1 dB coupling is achieved (Fig. 3(a)). The measured response degrades at frequencies above 20 GHz due to load termination mismatch. The phase (Fig. 3(b)) for both the coupled and thru ports is very linear with respect to frequency. The input

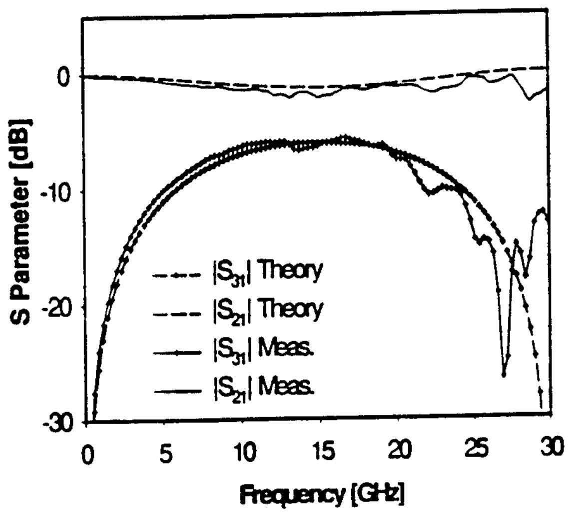

Fig. 3(a). Thru (S_{21}) and coupled (S_{31}) magnitude responses for a 6-dB CPW coupled-line device.

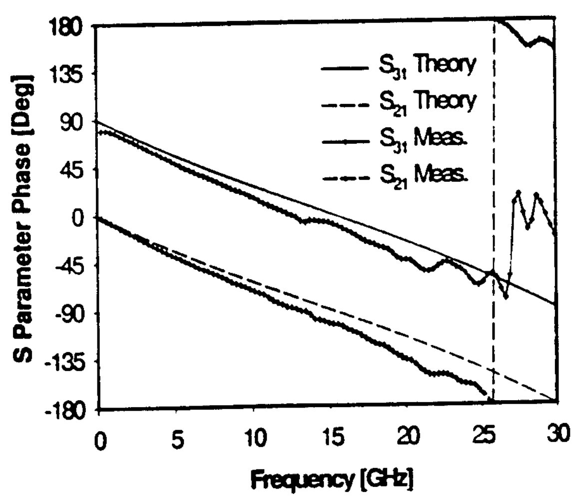

Fig. 3(b). Thru (S_{21}) and coupled (S_{31}) phase responses for a 6-dB CPW coupled-line device.

reflection $|S_{11}|$ is between -15 dB and -25 dB in the passband. The isolation $|S_{41}|$ is < -20 dB throughout the passband.

. SINGLE-SECTION BPF USING 3-dB COUPLER GEOMETRY

To demonstrate higher coupling levels and test the high-aspect fabrication process in a quick and simple manner, a two-port CPW quarter-wave coupled-line device with shorted coupled-section terminations was tested (see Table I). The coupling level necessary for a single-section 3-dB coupler may also be used in the design of a single-section coupled-line bandpass filter [6]. This filter is phase-velocity compensated with a meandering coupling gap to increase the effective capacitance "seen" by the odd-mode wave. The velocity ratio in this device is 1.175, requiring the meander path length to be 17.5% longer than the overall linear coupled section length.

The 3-dB BPF device was fabricated using the previously described LIGA process (Fig. 4(a) & 4(b)). Ideally, the filter section's $|S_{21}|$=0 dB at 15 GHz. The DUT had a measured $|S_{21}|$=~ -0.4 dB in the passband (Fig. 5(a)), due to reflection and losses. Upon examination of $|S_{11}|$ and $|S_{21}|$, we estimate ~-0.37 dB due to loss and ~-0.03 dB due to incorrect coupling level (not -0.4 dB). An equation relating coupling level for a short-circuit terminated quarter-wave section to $|S_{21}|$ in the passband was derived based on material in [6]:

$$\frac{b_2}{a_1} = 2C\sqrt{1-C^2}$$

where b_2/a_1 is S_{21} and C is the coupling level in the coupled-line section. C=0.736 for the filter, corresponding to an approximate -2.66 dB coupling level. This coupling level is higher than practically achievable using thin-film uniplanar fabrication methods and is greater than -3 dB due to the over-plated height and resulting extra capacitance of the coupled lines. The measured $|S_{11}|$ exhibits the general shape of the theoretical curve but includes calibration artifact. As with the 6-dB 4-port device, the transmission phase is highly linear (Fig. 5(b)).

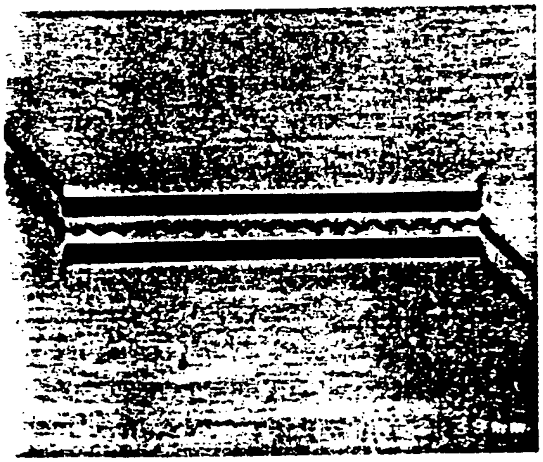

Fig. 4(a). SEM micrograph of a microfabricated thick-metal single-section CPW BPF.

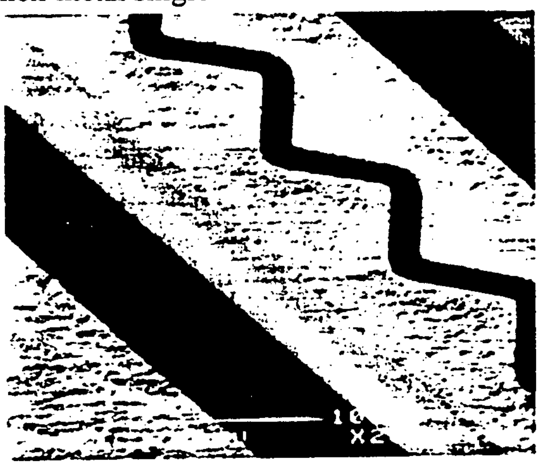

Fig. 4(b). SEM micrograph of 3-dB coupled lines in thick-metal single-section filter.

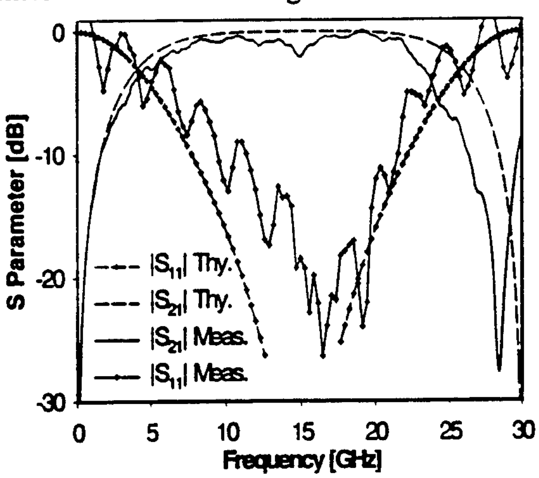

Fig. 5(a). Reflection ($|S_{11}|$) and Thru ($|S_{21}|$) responses for a 3-dB coupled-line filter section.

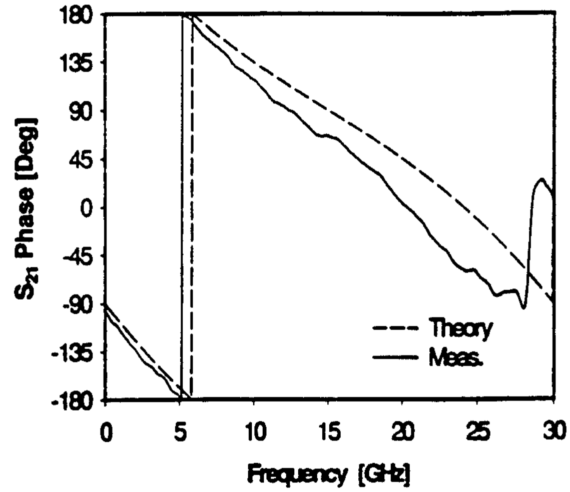

Fig. 5(b). Thru (S_{21}) phase response for a 3-dB coupled-line filter section.

CONCLUSION

Highly-coupled quarter-wave CPW couplers and filters fabricated using LIGA micromachining were presented. These novel devices demonstrate up to -2.66 dB coupling without requiring physical geometries that are limited by fabrication-yield degradation. To the knowledge of the authors, these are the first single-section CPW microwave couplers to achieve this level of coupling using a single lithography layer.

REFERENCES

1. C.L. Holloway et al., *IEEE Trans. Micro. Theory Tech.*, vol. 43, pp. 2695-2701, 1995.
2. E. W. Becker et al., *Microelectron. Eng.*, vol. 4, pp. 35-36, 1986.
3. H. Guckel et al., *Proc. SPIE-Int. Soc. Opt. Eng.*, vol. 2194, pp. 2-10, 1994.
4. T.L. Willke et al., *IEEE Trans. Micro. Theory Tech.*, vol. 45, pp. 1681-1688, 1997.
5. Tippet et al., *IEEE Trans. Micro. Theory Tech.*, vol. MTT-30, May 1982.
6. D.M. Pozar, Microwave Engineering. Reading, MA: Addison-Wesley, 1990.